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# ON SOME MAGNETOHYDRODYNAMIC EFFECTS IN COMETS

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# ON SOME MAGNETOHYDRODYNAMIC EFFECTS IN COMETS

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By
Z.M. Ioffe

## SUMMARY

A general pattern of magnetic field-carrying solar wind flow past a comet is considered. Slamming of rays is explained by the velocity gradient in the flow behind the shock wave. The acceleration is found, which is imparted to plasma in the squeezing out process from the magnetic tubes of force (ray model). Its value is in accord with the observation data. It is shown that a narrow region of intensified magnetic field appears at the interface between the comet and the solar wind.

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Presented in the works [1,3] is a general pattern of solar wind flow past the comet. It is considered that the magnetic field imparts to comet's and solar wind plasma a quality of continium, and with that its role ends. Undoubtedly, such a consideration may be accepted as the first approach to the reality. Utilizing its results we shall examine some of magnetohydrodynamic effects in the comets.

1. General Pattern Of The Flow With Magnetic Field. A collisionless shock wave forming up-stream from comet's head [1-4] is analogous to the wave forming ahead of the magnetosphere. The transition region between the wave and the surface bounding the comet's plasma will be of the same nature as the transition region between the shock wave and the magnetosphere, i.e. turbulent plasma flow statistically directed from the Sun, and a turbulent magnetic field, must be observed in it. The way interaction of this flow with comet's plasma takes place cannot yet be considered as sufficiently clear, but the following macroscopic pattern, being a combination of Alfvén's poit of view [5], Axford's assumption about the existence of a shock wave [4] and the idea of the source [1], is quite acceptable.

Behind the shock wave, in the velocity field, the magnetic lines of force, will bend on account of velocity gradient encompassing the comet's head. The nature of the bend is shown in Fig. (1), analogous to Fig. 1 from [6]. Apparently, a component will generate independent of the original field direction parallelwise to the velocity. Parts of lines of force, recumbent in the neighbourhood of line 00', move initially only at the expense of diffusion, as the velocity in the point A is zero. The ends of the lines of force will be approaching the line 00' as if they were slamming.

The comet's ions originating in the magnetic field, are subject roughly speaking to the action of two forces: the hydrodynamic pressure, creating the flow pattern in the first approximation [2], and the magnetic pressure, owing to which "particles could be squeezed out of the magnetic tubes of force like a tooth astefrom a tube pressed on the side" [7]. This force induces an additional acceleration, the magnitude of which we shall evaluate below. Moving along the lines of force (along neutral tubes, according [8]), the ions "reveal" so to speak the turbulent structure of the magnetic field, emerging after the passage of the collisionless shock wave, which explains the spatial structure of comet's radial system.

2. Acceleration Of Comet Plasma. The acceleration, communicated to particles during their "squeezing out" of the magnetic tubes of force, may be evaluated by the following method. The equation of motion of plasma unit volume along the field lines influenced by the magnetic pressure gradient will be written [9] as:

$$\rho \frac{d\vec{V}}{dt} = -\vec{\nabla} \frac{H^2}{8\pi}.$$

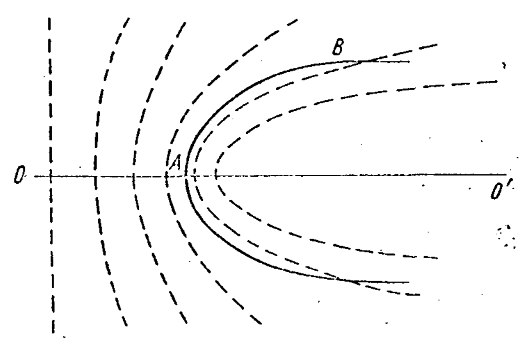

Figure 1.

We shall consider that there is a spherical symmetry within the range of a sufficiently small angle $\alpha$. The distance from comet's nucleus, in present case the center of symmetry, will be denoted by $l$. Then the equation of motion will be written as follows:

$$\rho \frac{dv}{dt} = -\frac{H}{4\pi} \frac{dH}{dl}.$$

From the condition of magnetic flow conservation we shall find $\frac{dH}{dl} = -2\frac{H}{l}$. Substituting this relation into the preceeding one, we shall obtain

$$H^2 = 2\pi\rho\, lq, \tag{1}$$

where $\frac{dv}{dt} = q$, $l$ is the distance between comet's nucleus and a certain point of the tail. For large comets $10^{10} \lesssim l \lesssim 10^{11}$ The density of particles in the tails $\sim 10^2$, which leads to $\rho \sim 0.5 \cdot 10^{-20}$ g/cm$^3$. Substituting these values into formula (1), we shall find the following relation between acceleration and field tension: $q = 6.6 \cdot 10^8 H^2$.

Let us estimate the magnitude of the magnetic field in the comet. $\rho_0$ is the solar wind pressure at the pont A, it is equal to $0.7 \cdot 10^{-8}$ for $\nu = 3 \cdot 10^7$ cm/sec and $\rho = 5 \cdot m_H$, where $m_H$ is the mass of the proton. Consideraing that $\frac{H^2}{8\pi} \sim \frac{1}{2} p_0$ we shall find $H^2 \sim 9 \cdot 10^{-8}$. Substituting this expression into the equation for q, we obtain $q \sim 60$ cm/sec$^2$, which agrees with the observations.

3. <u>Intensification Of Magnetic Field At Comet-Solar Wind Interface.</u> A tangential break occurs when solar wind flows past the comet at the interface. Thus an incompressible fluid the square of rate of the velocities $\left(\frac{v_f}{v_w}\right)^2 = \frac{\rho_w}{\rho_f}$, where $\rho_w$ is the density of original source (comet), $\rho_f$ is the density of streamline flow (solar wind) [1]. From Bernulli's equation and the condition of pressure equality at the interface, we shall obtain for a compressible fluid relation $\left(\frac{v_f}{v_w}\right)^2 = \frac{\rho_w}{\rho_f} \frac{(\gamma_w - 1)\gamma_f}{(\gamma_f - 1)\gamma_w}$, whence we shall find the velocity jump:

$$v_f - v_w = v_f \left\{ 1 - \left[ \frac{\rho_f}{\rho_w} \frac{(\gamma_f - 1)\gamma_w}{(\gamma_w - 1)\gamma_f} \right]^{1/2} \right\}, \qquad (2)$$

where $\gamma_f$ and $\gamma_w$ are the isentrope indicators respectively for comet and solar wind media. When $\rho_w \gg \rho_f$, it may be seen from (2) that $v_f - v_w \approx v_f$.

In the magnetic field, which generally speaking is not parallel to the interface (Fig.1) the velocity jump creates the formation of a "scissor" type break [10]. This break does not meet the conditions imposed on the fixed magnetohydrodynamic breaks, and therefore will disintegrate.

The investigation following below is relative to the disintegration of a plane break, but the conclusions remain valid also for the uneven break, since the same mechanism acts locally.

In the incompressible fluid the "scissor" break disintegrates into two Alfvén breaks, moving to the left and right from the initial position, and a contact break immobile relative to the medium (Fig.2).

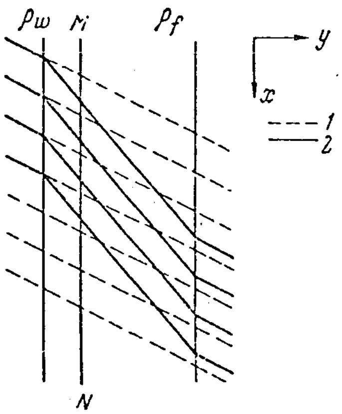


Fig.2.

MN is the plane of the initial break; 1) field line at the initial moment of time; 2) field lines for a time interval t

Using the conditions for the magnetohydrodynamic breaks [11], assuming $\rho$ = const and considering that in contact break the field and the velocity are continuous, we shall find that the field in the interval between two Alfvén's breaks increases by a quantity

$$\Delta H_x = (v_f - v_w)\frac{(4\pi\rho_f\rho_w)^{1/2}}{\rho_f^{1/2} + \rho_w^{1/2}}. \qquad (3)$$

(In the chosen system of coordinates the velocity is parallel to axis x, while axis y is perpendicular to the break plane). On condition that $\rho_w \gg \rho_f$ equality (3) is simplified: $\Delta H_x \approx (4\pi\rho_f)^{1/2} v_f$. The width of the region with amplified field $\lambda$ will be of the order of $v_{A1}\cdot t$, where $v_{A1} = \frac{H_y}{(4\pi\rho_w)^{1/2}}$, $t$ is the time of motion, approximately equal to $\frac{L}{v_w}$, where L is the distance, counted off from the nucleus along the tail of the first type, $\bar{v}_w$ is the mean motion velocity of tail's matter. The quantities $\rho_w, \rho_f, v_w, v_f, H_y$, entering into the expression for $\lambda$ and $\Delta H_x$, vary along the interface. Let us estimate $\Delta H_x$ and $\lambda$ according to order of magnitude. With the density of unberturbed solar wind 5 cm$^{-3}$ and velocity $3\cdot 10^7$ cm/sec its density in g/cm$^3$ and the velocity at the interface are included within the limits of $0.33\cdot 10^{-23} \leqslant \rho_f \leqslant 2.8\cdot 10^{-23}$ (at $\gamma_f = 2$ ); $v_f \leqslant 2.9\cdot 10^7$ . Then $\Delta H_x \leqslant 1.9\cdot 10^{-4}$.

Let us estimate the value of $\lambda$. On the interface between the points A and B the field is almost parallel to the velocity; therefore we shall consider that at the point B the $\lambda$ is near zero. The pressure of the area AB drops by almost one order, whereas, if we consider $\frac{H^2}{8\pi} \sim p_1$ , the field intensity drops by almost 3 times. The inclination of the field line to interface is determined by the inclination of the rays. In the vicinity of the point B it is about equal to 15-20°. Thus, for the initial part of the tail $H_y \approx 0.34\cdot 10^{-4}$ и $v_{A1} = 3.7\cdot 10^4$ . For the value of $\lambda$, we have $\lambda \lesssim 3.7\cdot 10^{-3} L$. since with the increase of the distance L the velocity $v_{A1}$ decrease.. (We assumed $\tilde{v}_w \approx 10^7$).

In the above-mentioned estimates we proceeded from the assumption of medium incompressibility. The disintegration of the "scissor" break in the compressible medium was investigated in [10], where it is assumed that the density of the two media, sliding against one another, are equal, while the density of the magnetic field has a normal component only to the plane of the break. Such a break is called symmetrical and in order to apply the results of [10] to the case of solar wind flow past the comet, it is imperative to make the following two suggestions: 1) the influence of the magnetic field's tangential component to the surface is insignificant and therefore may be neglected: 2) the asymmetrical break in a compressible fluid is reduced to a symmetrical one, just as in the incompressible, by means of a substitution:

$$v_x = (v_f - v_w)\frac{2}{1+\left(\frac{\rho_w}{\rho_f}\right)^{1/2}}.$$

Here $v_x$ is the velocity with which the medium $\rho_w$ must move relative to a medium with the same density, so that the perturbations in the medium $\rho_w$ coincide with the previous ones. On the average the ratio of $\rho_w/\rho_f$ is $1.5 \cdot 10^3$, then $v_x = \frac{v_f - v_w}{20} \approx \frac{v_f}{20}$.

According to [10], two waves will move from the position of the initial break, on both sides: a gas-dynamic shock wave and an ordinary rarefied wave. The computation of flow is made numerically, and the connection of the parameters behind the waves with the parameters of the initial state is given in the form of graphs. We shall determine on the basis of [10] the perturbed area's velocity expansion and the accretion of the magnetic field for a certain middle point of the interface (point B).

The expansion velocity of the perturbed area is $U = v_A\left[\frac{(\alpha^2 + Y)s_0}{\gamma(1-\alpha^2)}\right]^{1/2}$ Here $\alpha^2 = \frac{\gamma-1}{\gamma+1} = \frac{1}{6}$ at $\gamma = 1.4$; $s_0 = \frac{a^2}{v_A{}^2} = 4\pi\frac{\gamma p}{H^2}$ is the ratio of the square of sound velocity to the square of Alfvén velocity. Since $\frac{H^2}{8\pi} \approx p$ for the point B $s_0$ is approximately equal to the unity. Y is the ratio of pressure behind the shock wave to the pressure in the unperturbed medium. For a given $s_0$ this quantity depends on the ratio of velocity jump at the break to the sound velocity (in our case it is necessary to take the ratio $v_x$ to the sound velocity). Let us estimate the sound velocity of the point B, taking into account that the pressure between A and B drops approximately by one order and considering the flow as isentropic. When the pressure at the point A is $0.7 \cdot 10^{-8}$, and the density is $0.45 \cdot 10^{-19}$, we shall find for the sound velocity at the point B c = $3.5 \cdot 10^5$ cm/sec. We shall find velocity $v_f$ at the point B from the Bernulli equation and the condition that the pressure between the points of A and B drops approximately 10 times. $v_f \approx 2.5 \cdot 10^7$, whence $v_x \approx 1.7 \cdot 10^6$. The ratio $\frac{v_x}{c}$ = 5, and from [10] it follows, that $Y \approx 7$, whence $U \approx 2.5\, v_A$.

According to [10], $\frac{\Delta H_x}{H_y}$ in the perturbed area at the indicated parameters, is approximately equal to 3.

Thus, we may see that the two above-mentioned methods obtained by different ways, are coinciding and it is possible to arrive at the following conclusion: there exists at the interface "comet-solar wind" a narrow area of increased magnetic field.

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